GEANT4 Muon Digitization in the ATHENA Framework

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Abstract

The aim of this note is to describe the Muon Digitization software packages, completely re-written to run in the ATHENA framework and to interface with the GEANT4 Muon Spectrometer simulation.

The Muon Digitization is the simulation of the Raw Data Objects (RDO), or the electronic output, of the Muon Spectrometer. In the present architecture, it consists of two steps: in the first step, the output of the detector simulation, the Muon Hits, is converted to Muon Digits, i.e., intermediate objects that can be fed into the reconstruction. In the second step, the Muon Digits are converted into RDO, the transient representation of raw the data byte stream.

In this paper we will describe the detailed implementation of the first step of the Muon Digitization, where the detector simulation output is "digitized" into Muon Digits, also referred as Reconstruction Input Objects (RIO). This procedure occurs separately for each Muon technology. The second step, which convert the RIO in the RDO (byte stream) is implemented in separate algorithms and documented in [1]. We will describe the fundamentals of the Muon Digitization algorithms, outlining the global structure of them, with some emphasis on the simulation of piled-up events, on the link to the Monte Carlo Truth and on the Digitization validation against the Monte Carlo information.

MUON DIGITIZATION

The Muon Digitization software has been recently rewritten to run in the ATHENA framework and to operate on the GEANT4 Hits. The goal of the Muon Digitization is to simulate the output signal of the ATLAS Muon Detector, starting from the output of GEANT4 detector simulation.

The new Muon Digitization consists of four algorithms in the ATHENA sense, one for each muon technology (MDT, RPC, CSC and TGC). It provides the production of collections of simulated Muon Digits out of Muon Hit collections from the GEANT4 simulation.

The Muon Digitization has been designed to be independent from the GEANT4 simulation. It relies only on the read-out geometry (provided by MuonGeoModel [2]) and on the detector-specific Muon Spectrometer Offline Identifier (OID) scheme [3].

Muon Hits

Hit production in GEANT4 is provided by the *Sensitive Detectors* classes. Each time a particle trajectory crosses a volume which can generate hits, the kernel is responsible for calling the corresponding Sensitive Detector, which implements the hit generation algorithms. Hence, the Sensitive Detector generates a list of hits, which are stored as output of the simulation procedure.

Hits have a very light content. They consist of a *Simulation Identifier* (SimID), a 32-bit integer in which the geometry information about the hit position is stored, plus the quantity to be digitized. Hits are collected using AthenaHitsVector containers, one for each Muon technology, where they are inserted in a random way (no sorting is performed at the simulation level). There are therefore four independent hit collections in the Muon Spectrometer per event, one for each technology.

Muon Digits

Muon Digits are the output of the first step of the digitization procedure. They resemble the detector output and are basically defined by the reconstruction group. In fact, the Muon Digits can be fed directly in the Muon Reconstruction, for this they are also referred as Reconstruction Input Objects (RIO). They are labeled by an OID which packs the geometry information. The additional geometry description of the detector elements are obtained from the MuonGeoModel *read-out* geometry([2]).

Infrastructure for Event Pile-Up

In addition of handling hits coming from a single bunch crossing, the digitization is also be able to handle *piled-up* collisions. Before performing the digitization, hits from several bunch crossings can be overlaid taking into account the global time of the hit, which is defined as the GEANT4 hit time plus the bunch crossing time with respect to the main crossing. Therefore, simulated GEANT4 hits can be read in together with previously generated minimum bias and cavern background events. The hit overlay and sorting

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according to the detector elements is then carried out and the digitization proceeds afterwards.

Association to Monte Carlo Truth

Any reference to the Monte Carlo information is lost after the digitization procedure, that is, the Muon Digits or the RDO do not carry any link (pointer, associations) to the original simulated particles. Such "links" are necessary to establish the Monte Carlo truth tracks and for validation purposes.

During the Muon Digitization, a separate object is recorded and can be persistified, to maintain the link to the original simulated particles at the digit or RDO level. The recorded object in question is a map of muon off-line identifiers to MuonSimData objects. The objects of type MuonSimData are not applicable to the real production running. However, they can be made persistent in the simulation of non pile-up situations and are useful to carry the associations to the original particles to the tracking stage.

Digit Validation

The XXXDigitValidation algorithms have been implemented in order to check the correctness of the digit production and of the digitization processes. The general method consists of comparing known ("true") track position with associated digit position (from MuonGeoModel) and to study the residual distributions. The Truth information is coming from the MuonSimData (as discussed in the previous paragraph, a separate object which can be stored together with the RawData, which maintains the link to the hits at the Digit/RDO level. The validation is performed generating single muon events in the barrel, with no physics processes activated but transportation. The output of each validation algorithm is a Ntuple which contains the main Digit/Truth parameters. The XXXDigitValidation algorithms are part of the RunTimeTest (RTT) ATHENA nightly control.

Figures from 1 to 4 show validation plots for each of the four muon technologies.

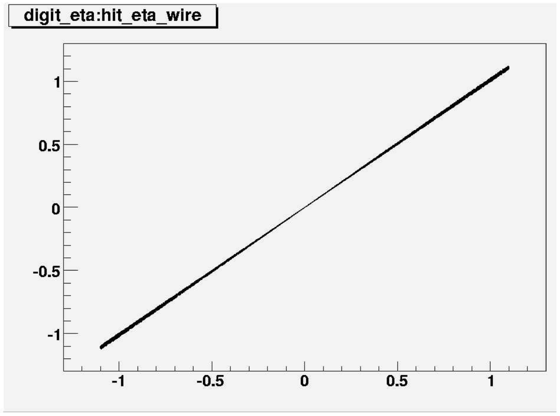

Figure 1: MDTDigitValidation: pseudorapidity from the digits as a function of the pseudorapidity of the hits.

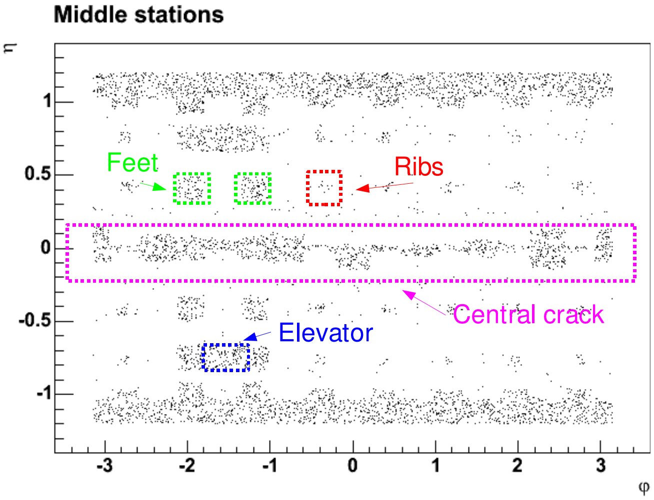

Figure 2: RPCDigitValidation: Scatter plot of η and ϕ directions of muons not producing any RPC Digit. The inefficiency regions correspond to Muon Spectrometer areas not instrumented with RPCs.

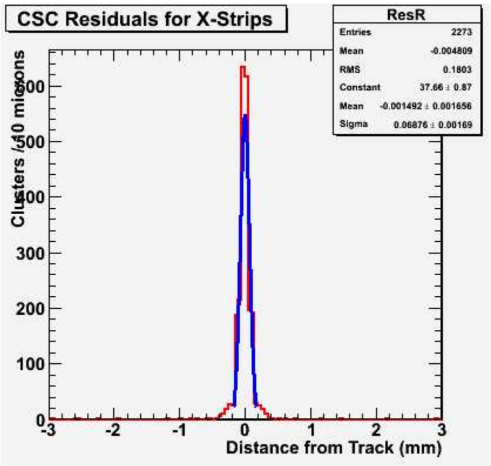

Figure 3: CSCDigitValidation including the simulation of the electronic ouptut. A clusterization is done and the residual is plotted. The residual is determined as the local distance from the cluster centroid to track in the plane of the wires. Muon tracks, originating from a fixed vertex (no vertex spreading), normally incident at centrer of the chamber (no magnetic field) are considered. The residuals from all the chambers are integrated in this plot. It is therefore an estimate of the intrinsic single hit resolution of the precision strips.

MDT_DIGITIZATION

The MDT_Digitization procedure converts the hit information from the GEANT4 simulation into an output which should resembles the output signal of the ATLAS detector. Each MDTSimHit contains a SimID, the impact parameter and the hit position in the global coordinate reference system. Each MDT Digit consisting instead of an OID, a TDC

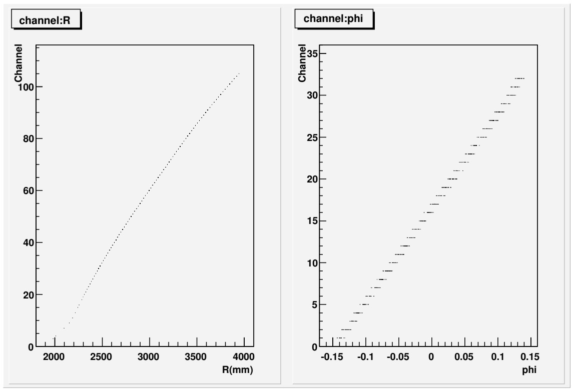

Figure 4: TGCDigitValidation: Channel number as a function of R postion (left) and ϕ postion (right). The relation between channel number and R postion is not linear, because of number of wire ganged depending on R position. On the other hand, channel postion for ϕ direction changes linearly with ϕ postion

count and, optionally, a ADC count.

Starting from the impact parameter, the driftRadius associated to the MDTSimHit, the MDT_Digitization performs several tasks:

1. conversion of the drift radius into a drift time,
2. calculation of the time structure of the event,
3. trigger match,
4. conversion of total time into TDC counts.

For the $r \rightarrow t$ conversion, two different ATHENA AlgTools have been implemented and are available in the MDT_Digitization package. Due to a modularity of the architecture, they can be selected via jobOptions setting the property DigitizationTool of the MDT_Digitizer algorithm. The first is a very detailed time-consumpting $r \rightarrow t$ procedure (MDT_Response_DigiTool) while the second is a fast drift distance to time conversion which relies on an external rt relation (RT_Relation_DigiTool). More information can be found in [4].

According to the different contributions to the pulse time, the drift time consists of the following components:

$$t_{tot} = t_{tof} + t_{bunch} + t_{prop} + t_{delay} + t_{drift} \tag{1}$$

The time of flight t_{tof} is obtained from the MDTSimHit in form of globalTime. The propagation delay t_{prop} is calculated from the position of the hit along the tube (obtained from the MuonGeoModel read-out geometry) and the signal propagation speed. Additionally, in case of pile-up, a bunch crossing offset t_{bunch} is taken into account.

The MDT chambers are equipped with TDCs (Time-to-Digit Converters) which measure the signal pulse time for each MDT passing a predefined threshold. To avoid not physical hit proliferation, the TDCs have a programmable dead time which is set to the maximum drift time of the tube [[5]] as shown in Figure 5. The same principle is reproduced in the digitization procedure.

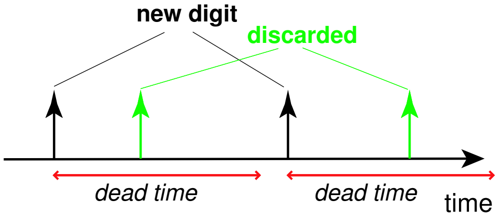

Figure 5: Dead time.

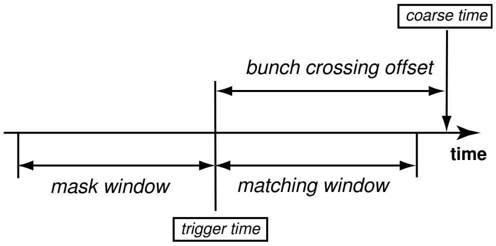

Figure 6: Time windows.

A trigger match criterion is applied to all the selected hits following the same procedure (as described in [[6]]). First, a trigger time t_{trig} is calculated as follows:

$$t_{trig} = t_{delay} + t_{avetof} + t_{bunchoffset}$$

where t_{delay} is the time entering the TDC time calculation 1 and t_{avetof} is the average time a particle at light speed need to reach the center of the chamber (an additional offset $t_{bunchoffset}$ allows the windows to be positioned with respect to the GEANT4 global time). Then, for every hit the time $t_{TDC} - t_{trig}$ is matched with the time windows:

- if the time of a hit falls within the *matching window*, a MDT_Digit is produced;
- a hit in the *mask window* produces a MDT_Digit which contains no TDC count and is flagged as *masked*;
- any hit outside the windows is discarded.

Depending on the sizes of the two windows it is possible to have *more that one hit per event per tube*, both will be stored. The TDC count is finally stored into the MDT digit object.

RPC_DIGITIZATION

RPC hits are generated by the RPCSensitiveDetector which assigns to them a Simulation Identifier (SimID), uniquely identifying the gas gap each hit is registered in. The position of the hit in the reference system of the gas gap is also stored, together with the time from the beginning of the event, i.e. the time of flight of the particle generating the hit.

When a particle generates an avalanche in an RPC, charge signals are induced (and detected) on the readout strips. A set of n adjacent strips with signals is called a *cluster* of size n. In RPC operation, due to possible signal induction on more than one strip, cluster sizes are in general greater than 1, with an average cluster size at working point typically of 1.3. This cluster simulation is done at the digitization level. The RPC_Digitization algorithm reproduces the observed cluster sizes by generating, when necessary, digits on strips adjacent to the one actually crossed by the particle.

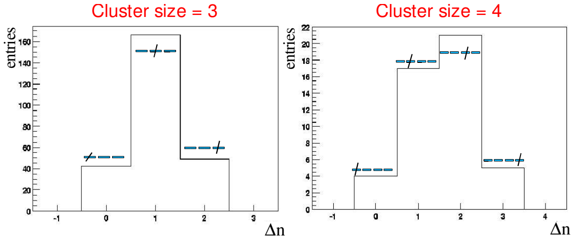

Figure 7: Experimental cluster spread distributions for cluster of sizes 3 and 4.

Cluster simulation is carried on in three steps:

1. experimental distributions are used to decide, according to the impact point of the particle along the strip, whether the cluster size will be 1 or 2.
2. experimental distributions are used to decide what the final size of the simulated cluster will be.
3. digits are created according to the results of the above steps.

Particular attention is paid to the way the additional digits are created around the one actually crossed by the muon. Figure 7 shows the cluster spread distributions. For each cluster of a given size, the plots count which strip was actually crossed by the muon. Upon each bin, the corresponding track/strip configuration is showed.

CSC_DIGITIZATION

The digitization in the CSC is the simulation of the charge distribution on the CSC cathode strips given a hit in the sensitive gas. The process also identifies the the strips numbers and their orientations. Thus after processing all the hits in the event, the CSC digitization outputs the list of digits into the transient event store from where they could be picked up by other algorithms. The object referred to as a CSC digit is nothing more than the compact identifier of a strip together with the charge on that strip and the hit time.

The second stage in the digitization is the simulation of the raw data, i.e., the output of the CSC electronics. This output consists of a number of ADC values determined by the sampling rate of the amplifier signal. The bi-polar shape of the signal, shown in Figure 8 is modeled according to the following equation:

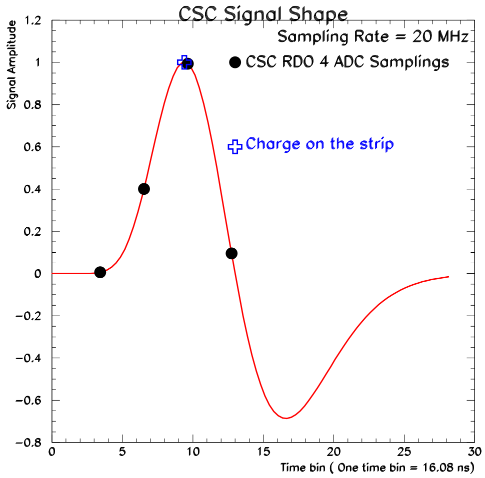

Figure 8: CSC amplifier signal shape. The signal can be sample at an adjustable rate and a voltage comparator gives the ADC value at each sampling. The charge on the strip is taken as the difference the maximum of positive lobe and the baseline. Finding the maximum and the baseline requires a fit to the ADC samplings. Then the calibration curve is also needed to convert the maximum to FemtoCoulomb.

$$ADCValue = \left(1.0 - \frac{z}{n+1}\right) z^n \exp\left(-z\right) \qquad (2)$$

where n is the number of amplifier integrations, and z is written as follows:

$$z = (samplingTime - startTime)/signalWidth \quad (3)$$

and signalWidth is the width of the positive lobe of the bipolar signal. The charge on the strip is taken as difference between the maximum of the positive lobe and the baseline (pedestal). In the simulation, the charge on the strip is known, as obtained from the hit digitization: the problem therefore consists of going from one charge value (in number of equivalent electrons or femtoCoulombs) to number N of ADC samplings (in ADC counts) at an assumed sampling rate — CSC data will be taken at a variable sampling rate. To this end, a conversion of the charge into ADC count is required; then the signal shape is normalized to the charge (in ADC counts) and sampled to generate the simuated raw data — the ADC samplings for each fired strip.

The conversion of the simulated charge on the strip into the ADC counts requires the calibration constants for the strip and the calibration curve. An example of a calibration curve for one strip in shown in Figure 9. Once the ADC samplings are simulated, they can either to written out in POOL or encoded in the byte stream using the format of the ROD.

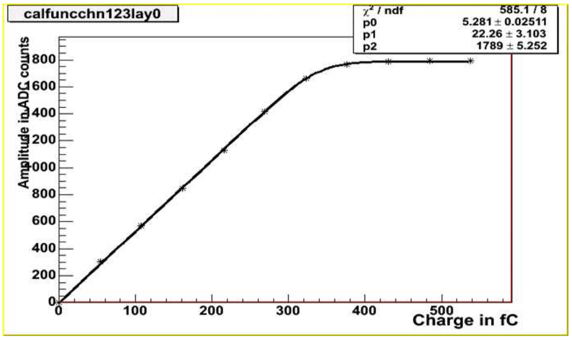

Figure 9: CSC calibatrion curve for one strips. The calibrations constants are written to and obtained form conditions databases.

TGC_DIGITIZATION

The main functionalities of TGC digitizer are the following:

- to create digits from GEANT4 hits,
- to simulate detector response (timing, detection efficiency, multi signals by a single hit).

TGC digitization simulates the following detector responses: multi hits due to tracks passing several wire gangs or strips and induced charge spread on cathode plane which may make signals in several strips, intrinsic time response due to variation of strength of electric field in a sensitive layer which depends on injection angle of charged tracks and signal propagation along wires and strips and detection efficiency (sensitivity) of wire gangs and strips.

The multi hits on the strips is made by the charge spread on the cathode plane which is induced by the avalanche around anode wires. Multi hits on wire gangs are generated when a charged track passes the boundary between two wire gangs. In addition, the cross talks between signal channels originating from readout electronics could be a source of multi hits. At the moment, this is not taken into account. Hit positions of R coordinate in TGC can be read by gangs of wires. Hit positions of ϕ coordinate in TGC can be read by strip. The digitization procedure occurs separately for these two channels.

The intrinsic time response is parametrized using standalone simulations and the parametrization had been confirmed by test beams. Figure 10 shows that an example of the distribution of time response of signals from wires. The response time depends on the incident angle of charged particles. Larger insistent angle gives shorter response time, this is because the particle can have larger possibility to pass the stronger electric field in which electrons can reach a wire in short time.

At the moment, the detection efficiency of chambers are averaged over their sensitive areas. However, the efficiency map of each chamber have been measured by the test bench with cosmic rays, therefore the use of the map will be implemented eventually for realistic simulation.

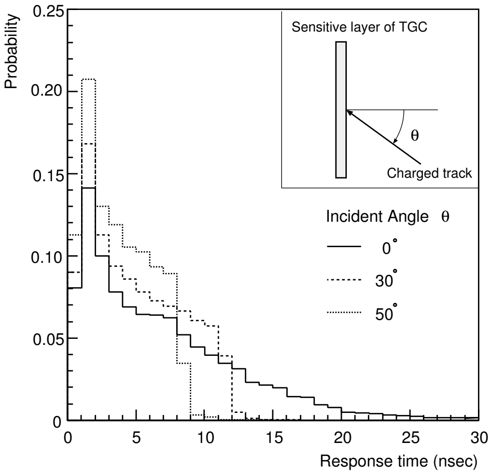

Figure 10: Simulated time response distribution of TGC as a function of incident angles of charged tracks. Larger angle gives shorter response time.

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